Pulsars Born in Open Stellar Clusters

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Abstract

For two nearby pulsars, formed close to the galactic plane, their host open stellar clusters have been found.

1 Birth site for pulsar B 2224 + 65.

Cordes et al. (1993) discovered the complex consisting of pulsar B 2224 + 65 and of the gaseous nebula "Guitar", the pulsar being located at the end of its "neck". The pulsar is specified by a great proper motion which may be due to its proximity to the Sun or, otherwise, it is a very peculiar object even among the pulsars. The only procedure used so far to measure the distance using the dispersion measure of the pulsar, $DM = 35.3$ ps/cm^{-3}, yields $D_0 \sim 1.95$ kps. There is, however, a ring of gas around the pulsar ionized by a shock wave (the density jump is characterized by a factor of $10 \div 12$ (see Kaplan & Pikelner, 1979)). Electrons which contribute to the dispersion measure of the pulsar may partly belong to this gaseous ring. Therefore, the value $D_0 \sim 1.95$ kps seems to be overestimated. The discovery of soft X–ray radiation from the nebula "Guitar", that contains the moving pulsar (Romani et al., 1997), also provides evidence for the complex to be close to the Sun. A more precise distance to the pulsar could be estimated from its trigonometric parallax when available.

Characteristic pulsar age is $t_c = 0.5\,P/\dot{P} = 1.12$ Myr (Taylor et al., 1993) where P is the pulse period, $\dot{P}$, its first derivative in seconds. Characteristic ages of pulsars are found to be systematically high. A real age is determined more precisely using the expression for so–called "kinematic age" (Smith, 1977):

$$t_k = 0.5\,\tau_D\,ln(1 + t_c/(0.5\,\tau_D)).$$

The parameter of magnetic field attenuation is estimated by us (Pskovskii & Dorofeyev, 2001) to be $\tau_D = 1.8 \pm 0.2$ Myr. Thus, kinematic age of pulsar 2224+65 is $t_k = 0.74 \pm 0.10$ Myr.

The position angle PA of the pulsar motion has been preliminarily found to be 52^o which indicates that the pulsar has arrived at its current site on the celestial sphere from the IIIrd quadrant, that is, from the area within $\alpha(19^h \div 22^h)$, $\delta(+70^o \div 65^o)$. To determine the site of its birth more accurately one needs to take into account systematic variations in pulsar radial velocity and proper motion, though its spatial velocity may be regarded as being constant.

If the pulsar has been moving towards the Sun for the past 0.7 Myr, it is likely to have started from the region close to an open stellar cluster localized not far from the Sun in the same quadrant. A possible candidate is cluster M 39 (NGC 7092).

2 Formulae for calculation of the pulsar starting site

A trajectory of motion for a pulsar having a constant spatial velocity is rectilinear, but its projection on the celestial sphere is an arc of a great circle. We shall use the rectilinear equatorial reference frame XYZ with the origin O at the point of observations (Fig. 1). The current position $\Pi(\alpha_o,\, \delta_o,\, 1950)$ of the pulsar belongs to the plane YZ. It corresponds to the position $\Pi(x_o,\, y_o,\, z_o)$ in the rectilinear frame, where $x_o = 0$, $y_o = D_o \cos\delta_o$, $z_o = D_o \sin\delta_o$. The components of the pulsar spatial velocity V are directed, correspondingly

$V_\alpha\,(V_\alpha,\, y_o,\, z_o)$ — parallel to the axis OX,

$V_\delta(0,\, y_o - V_\delta\, \sin\delta_o,\, z_o + V_\delta\, \cos\delta_o)$ — along the meridian,

$V_r(0,\, y_o + V_r\, \cos\delta_o,\, z_o + V_r\, \sin\delta_o)$ — along the ray $\Pi\, O$.

These components are obtained in km/s if expressed in terms of observational values $V_\alpha = 4.74\, D_o\, \mu_\alpha$, $V_\delta = 4.74\, D_o \mu_\delta$, $V_t = 4.74\, D_o\, \mu$ (the tangential pulsar velocity for the current epoch), $V_r = V\, \cos\zeta$. Here μ, μ_α, μ_δ are the proper motion and its components along the axes OX and OY expressed in arc seconds per year and corrected for the motion of the Galaxy and for the motion with respect to the Sun; ζ is the angle between the rotational axis of the pulsar and the direction towards an observer. The expression $V_r = V\, \cos\zeta$ follows from the result established earlier (Tademaru, 1977; Pskovskii & Dorofeyev, 1987); the directions for both V and V_t are supposed to be known from the "rule of signs" for ζ (Pskovskii & Dorofeyev, 2001).

The system of equations for a straight line parallel to the vector

$$V(V_\alpha, V_r \cos\delta_o - V_\delta \sin\delta_o, V_r \sin\delta_o + V_\delta \cos\delta_o)$$

is given by

$$\frac{x}{V_\alpha} = \frac{y - y_o}{V_r \cos\delta_o - V_\delta \sin\delta_o} = \frac{z - z_o}{V_r \sin\delta_o + V_\delta \cos\delta_o} = 0.978\, t_k = \vartheta, \quad (1)$$

where x, y, z are the rectilinear coordinates of a pulsar at a starting moment (in parsecs), $0.978 = \vartheta/t_k$ is a dimensional factor in units of ps/km/s. By their sense, the values t_k and ϑ are negative. As the value D_o is not known, and neither are the velocity and its components expressed in terms of D_o, the system (1) can be transformed as follows:

$$\begin{aligned}
x'/D_o &= 4.74\vartheta\mu_\alpha, \\
y'/D_o &= (1 \pm 4.74\vartheta\mu\cot\zeta)\cos\delta_o - 4.74\vartheta\mu_\delta\sin\delta_\delta, \\
z'/D_o &= (1 \pm 4.74\vartheta\mu\cot\zeta)\sin\delta_o + 4.74\vartheta\mu_\delta\cos\delta_\delta, \\
(D'/D_o)^2 &= (x'/D_o)^2 + (y'/D_o)^2 + (z'/D_o)^2.
\end{aligned} \tag{2}$$

D' is the pulsar distance at a starting moment. The equatorial coordinates for the starting moment α', δ' are given by:

$$\begin{aligned}
\alpha' &= \alpha_0 + \frac{y'}{\cos\delta'}\arcsin\left(\frac{x'}{D'}\right), \\
\delta' &= \arctan(\frac{z'}{y'}).
\end{aligned}$$

The coordinates $x'_M, y'_M, x'_M; \alpha'_M, \delta'_M$ for cluster M 39 at the moment $-t_k$ are obtained using the formulae (1).

3 The birth site of pulsar B 2224+65

The parameters of pulsar B 2224+65 and of the open stellar cluster M 39 which are currently observed, as well as those calculated for the moment of birth, are shown in the second and the third columns of Table 1, respectively. The other columns of the Table contain findings for the objects to be reviewed below. The nomenclature of the rows is explained in the text. The data for the pulsars are given according to Taylor et al. (1993), and those for the open stellar clusters, according to Rastorguev & Glushkova (1999). The angle ϑ has been determined by means of our approach (Pskovskii & Dorofeyev, 1998).

Since the distance D_o to pulsar B 2224+65 is not known, the values of x'/D_o, y'/D_o, etc. are to be calculated. For the rest of the pulsars and for all the stellar clusters the values x', y', etc. have been determined as the distances D_o are available for them.

Because of significant errors involved in the technique of determining initial coordinates of a pulsar using its current estimated values μ, V_r, D_o, and ϑ, one can anticipate, in the best case, but the full (or a partial) superposition of an error box of a pulsar and that of a stellar cluster.

In our case, the distance to pulsar B 2224+65 estimated at the moment of birth cannot be matched with that for the stellar cluster M 39.

Table 1

Objects	PSR B2224+65	M39	PSR B192929+10	NGC
$l_0,\ b_0$	108.6, +6.8	92.5, -2.3	47.4, -3.9	36.1
$\alpha_0\,(h,m)$	22^h24^m	$21^h30.4^m$	$19^h29.9^m$	18^h
$\delta_0\,(^\circ)$	+65.34	+48 .22	+10.88	+
$\mu_\alpha\,(''/yr)$	0.146±0.003	=0.0504±0.0013	0.096±0.006	0.000
$\mu_\delta\,(''/yr)$	0.113±0.003	-0.016±0.003	0.050±0.004	0.002
$\mu\,(''/yr)$	0.185±0.003	0.0191±0.0013	0.108±0.006	0.002
$\varsigma\,(^\circ)$	41±3.0	-	24.4±3.0	
$\phi\,(^\circ)$	-	1.5	-	1
$D_0\,(pc)$	(200 ± 50)	350±100	170±40	380
$V_t\,(km/s)$	(200 ± 30)	32±7	90±20	4±
$V_r\,(km/s)$	(-230 ± 30)	-7.5±5	-190±50	-2
$V\,(km/s)$	(-300 ± 40)	33±7	210±50	30
$t_k\,(Myr)$	1.12	-	3.09	
$t_c\,(Myr)$	0.74±0.010	-	1.34±0.16	
ϑ	+0.74±0.010	-	-90±30	
$(x'/D_0)\,,\ x'\,(pc)$	(-0.49 ± 0.07)	12±6	400±80	0±
$(y'/D_0)\,,\ y'\,(pc)$	$(1.13 \div 0.07)$	220±90	30±50	410
$(z'/D_0)\,,\ z'\,(pc)$	(1.41 ± 0.010)	280±110	410±80	40
$(D'/D_0)\,,\ D'\,(pc)$	(1.87 ± 0.09)	360±100	3.7±20	410
$\delta'\,(^\circ)$	51±11	53±33	3.7±2.0	1.4
$\Delta\alpha'\,(h,m)$	$1^h07^m \pm 32^m$	$+12^m \pm 9^m$	$54^m \pm 18^m$	$0 \pm$
$\alpha'\,(h,m)$	$21^h17^m \pm 32^m$	$21^h45^m \pm 9^m$	$18^h36^m \pm 18^m$	$18^h25.5$

Therefore, the knowledge of possible uncertainties in α' and δ' is of great importance. To estimate them, the value of D'/D_o was suggested to possess a relative error which corresponds to the "bb" class in the classification proposed by Taylor et al. (1993), that is, 46 per cent. Errors of the values in the formulae have been suggested to be mean–square ones deduced from expressions for corresponding functions.

The error box for the stellar cluster M 39 has been calculated taking into account the angular diameter of the cluster having an extended corona with a diameter of $\sim 1.5^o$ (Artiukhina, 1970; Barkhatova & Pylskaya, 1978).

Fig. 2 shows the error boxes of these objects to be partly superimposed at the starting moment of the pulsar. The pulsar therefore can be considered to be at the distance D' at the moment in question, this distance corresponding to cluster M 39. This fact allows us to calculate the values D_o, V, V_t, and V_r for the pulsar. The findings are shown in Table 1 in brackets. The current distance to the pulsar, $D_o = 200 \pm 50$ ps, is obtained to be dramatically small, whereas kinematic parameters are shown to have rather common values. A dispersion measure of the pulsar in such a case is mainly due to electrons in a shock wave rather than to interstellar medium.

A spatial trace of the open stellar cluster M 39 (Fig. 2) is far shorter than that of pulsar B 2224+65. The distance to M 39 has remained practically the same, but the directions of pulsar and cluster motions are almost opposite.

Taking into account that M 39 is presumably a member of a kinematic group in Ursa Major (Lloyd Evans & Meadows, 1964; Eggen, 1965), an error box of the pulsar starting position proves to lie completely inside a field of the group. Unfortunately, it is impossible to determine kinematics of the object before the start, hence we cannot establish with certainty whether it belongs to the group or not.

4 The birth site of nearby pulsar1929+10

The coincidence of the birth site of pulsar B 2224+65 with the field of the stellar cluster M 39, however, does not exclude the possibility that some single pulsars may be produced outside stellar clusters. A number of young single pulsars, namely B 0531+21, B 0833-45, B 0611+22, B 0656+14, etc., which have not travelled very far from their starting points are not related to any stellar clusters. Some pulsars are found to start at high galactic z–coordinates (Pskovskii & Dorofeyev, 2001). From statistical findings correlations were shown to exist among young pulsars and stellar associations (Mdzinarishvili, 1997). In addition, pulsars discovered in globular stellar clusters belong to a quite specific group, as well as millisecond pulsars and those in binary systems.

Let us consider other pulsars which are close to us at the present time and which have well established estimates of proper motion, the distances D_o, and ages within the limits $0.7 < t_k < 1.5$ Myr. In addition to pulsar B 2224+65 considered above, these conditions are met for the two more pulsars, B 1929+10 and B 1133+16, the latter having unprecedented proper motion. Pulsar B 1133+16 is believed to have been born at a high galactic latitude, both for $V_r > 0$ and for $V_r < 0$, so it has no host stellar cluster.

Unlike pulsar B 2224+65, determinations of the birth sites of the two pulsars mentioned above are based on distances established rather well by Taylor et al. (1993). The positions of these pulsars at a starting moment have been calculated using formulae (1).

The data concerning a birth site of the pulsar and the parameters of its host cluster NGC 6638 are given in the corresponding columns of Table 1. The value of ζ has been estimated by our technique (Pskovskii & Dorofeyev, 1998). Cluster NGC 6633 has low proper motion, its error box lying almost entirely within that of pulsar B 1929+10 at the moment of its start (Fig. 3).

5 Conclusion

It has been shown that two nearby pulsars, which started from the galactic plane, may have been related, at a moment of their birth, to open stellar clusters. It is worthwhile pointing out that the both pulsars were reported to be weak sources of X–rays (Wang et al., 1993; Cordes et al., 1993).

There is good reason to believe that actually there are more pulsars related to open clusters. This can be deduced from the work of Mdzinarishvili (1997) containing evidence for the correlation of young pulsar ($t_c < 2$ Myr) distribution close to the galactic plane with that of O–associations in the vicinity of the Sun.

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Figure captions

Fig.1. Projections of a pulsar radial velocity V_r and of the components V_α and V_δ of a pulsar tangential velocity V_t on axes in the rectilinear equatorial reference frame X, Y, Z. The case of $V_r > 0$ is assumed. The following designations are used: $\Delta y_1 = V_\delta \cos\delta_0$, $\Delta z_1 = V_\delta \sin\delta_0$, $\Delta y_2 = V_r \cos\delta_0$, $\Delta z_2 = V_r \sin\delta_0$.

Fig. 2. Positions of pulsar B 2224+65 (empty squares) and of the open stellar cluster M 39 (empty circles) in the sky at the present time. For the pulsar starting moment the objects are indicated correspondingly by filled squares and filled circles which lie in the centres of their error boxes. The dashed line stands for the error box of the cluster; the continuous line, for the pulsar. The heavy line signifies the galactic equator. Coordinates are given for the epoch 1950.0.

Fig. 3. Positions of pulsar B 1929+10 and of the open stellar cluster NGC 6633 in the sky. The designations are the same as to Fig. 2.